Dust in the Universe at 2<z<4:
Results and Expectations

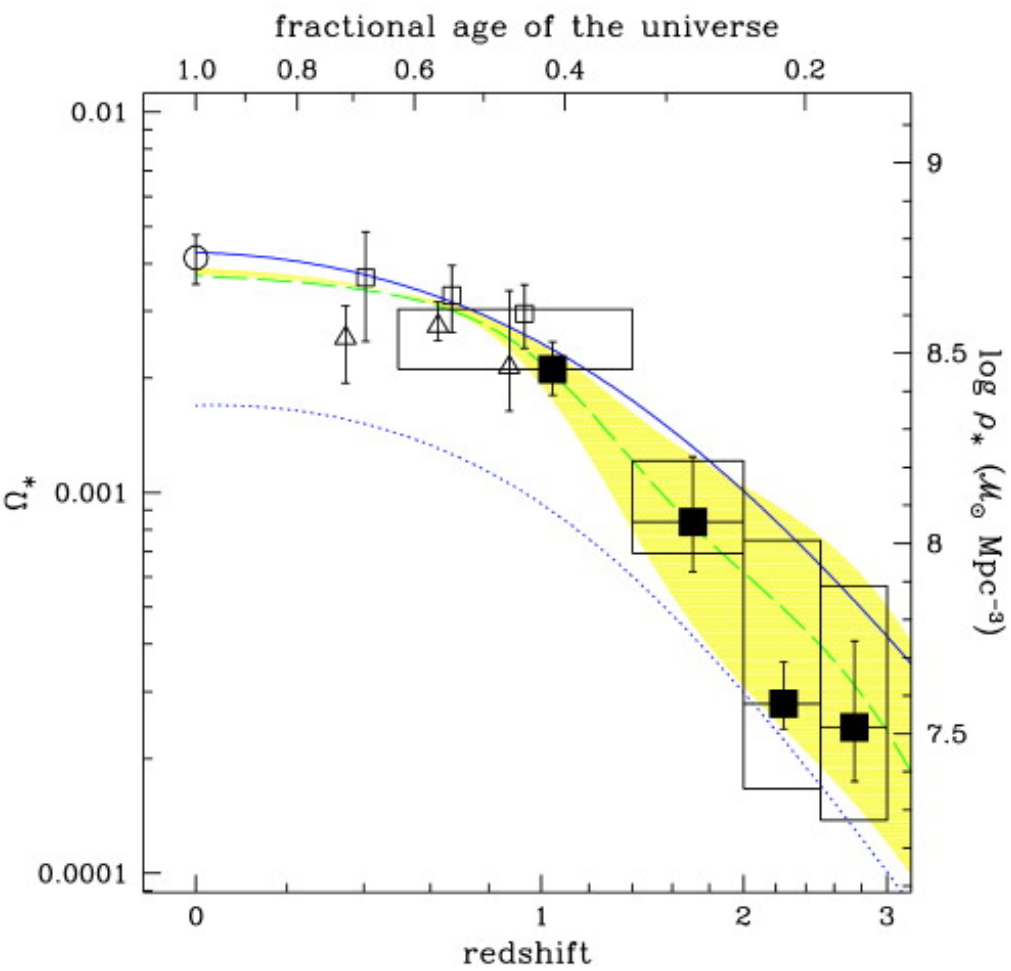
Ranga-Ram Chary
Spitzer Science Center
rchary@caltech.edu; 8 June 2004

- Required to provide an accurate census of nucleosynthetic and accretion contribution from the first generation of AGN and galaxies.

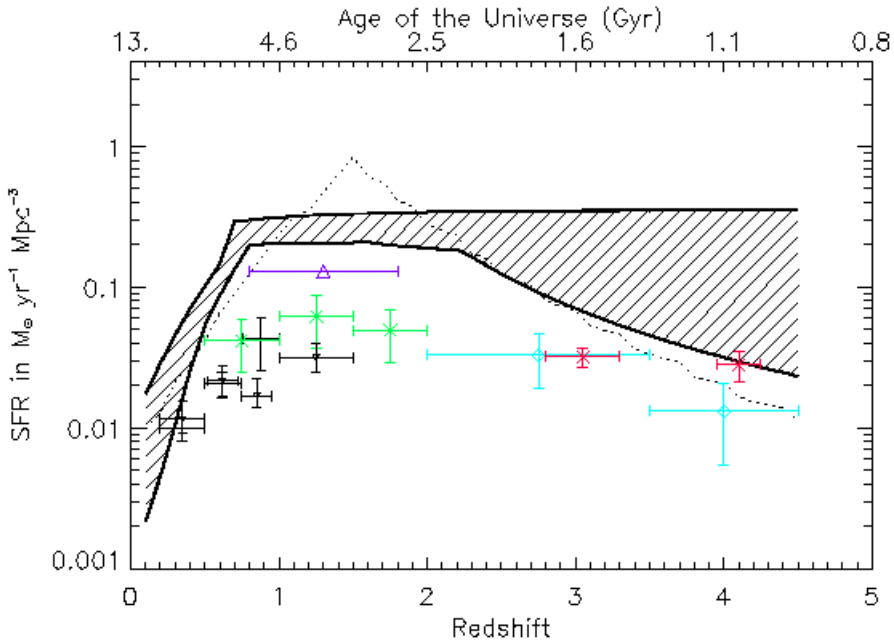
- More specifically, to identify the progenitors of the most massive galaxies in the local Universe.

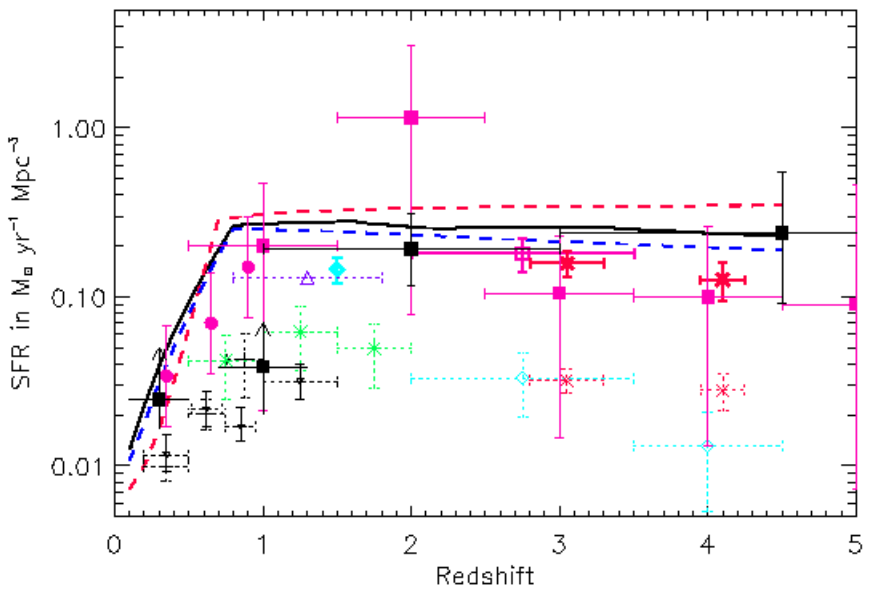
- Primary constraints are from SCUBA/MAMBO galaxy counts as well as FIRAS/CIRB spectrum.

- However, 80% of the CIRB (+CXB) comes from 0<z<1.5 and most of the mass is set in place between 0<z<2

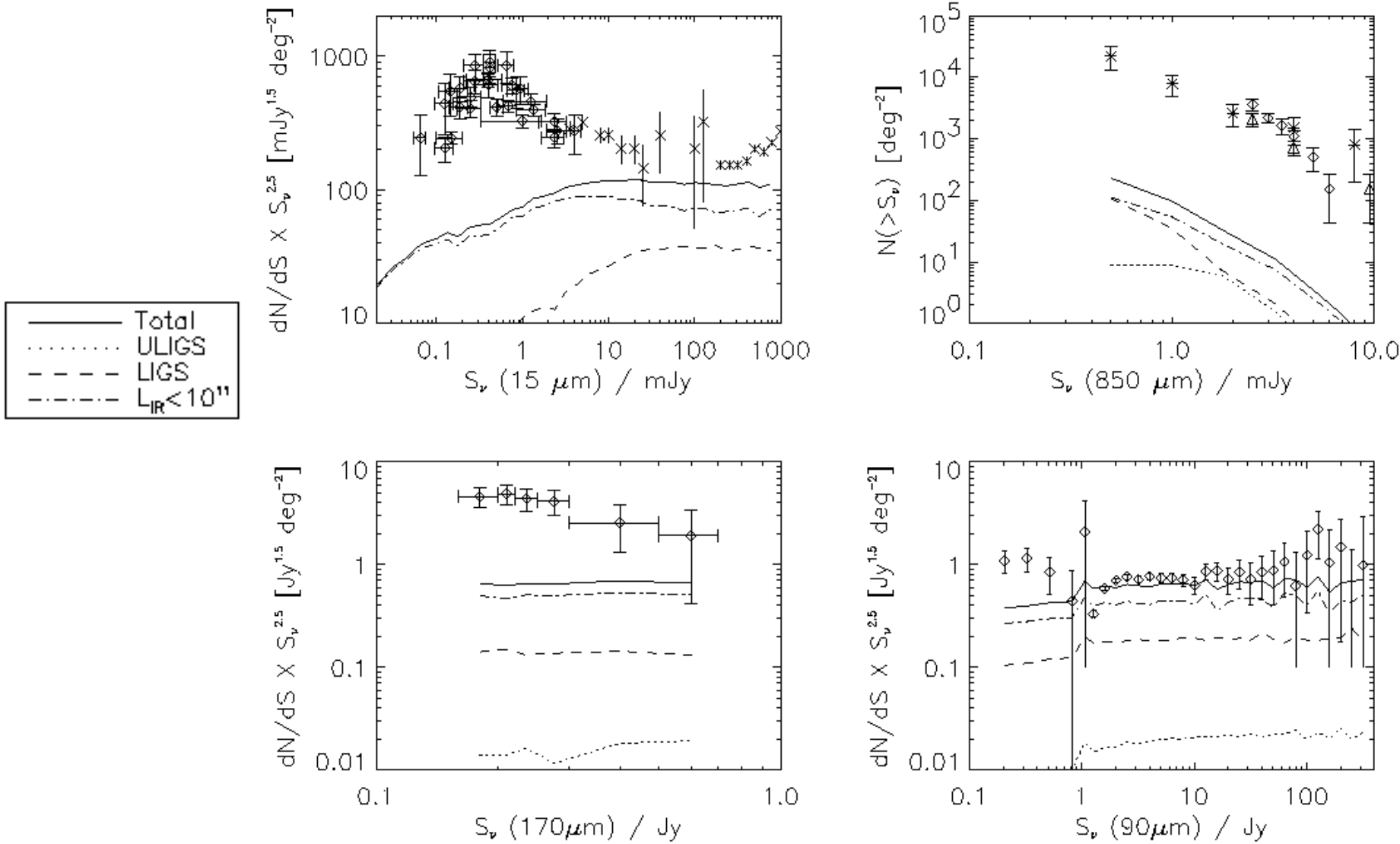


Observational Constraints from Dickinson et al., Glazebrook et al.





Empirical Constraints: Chary&Elbaz 2001, Xu et al. 2001

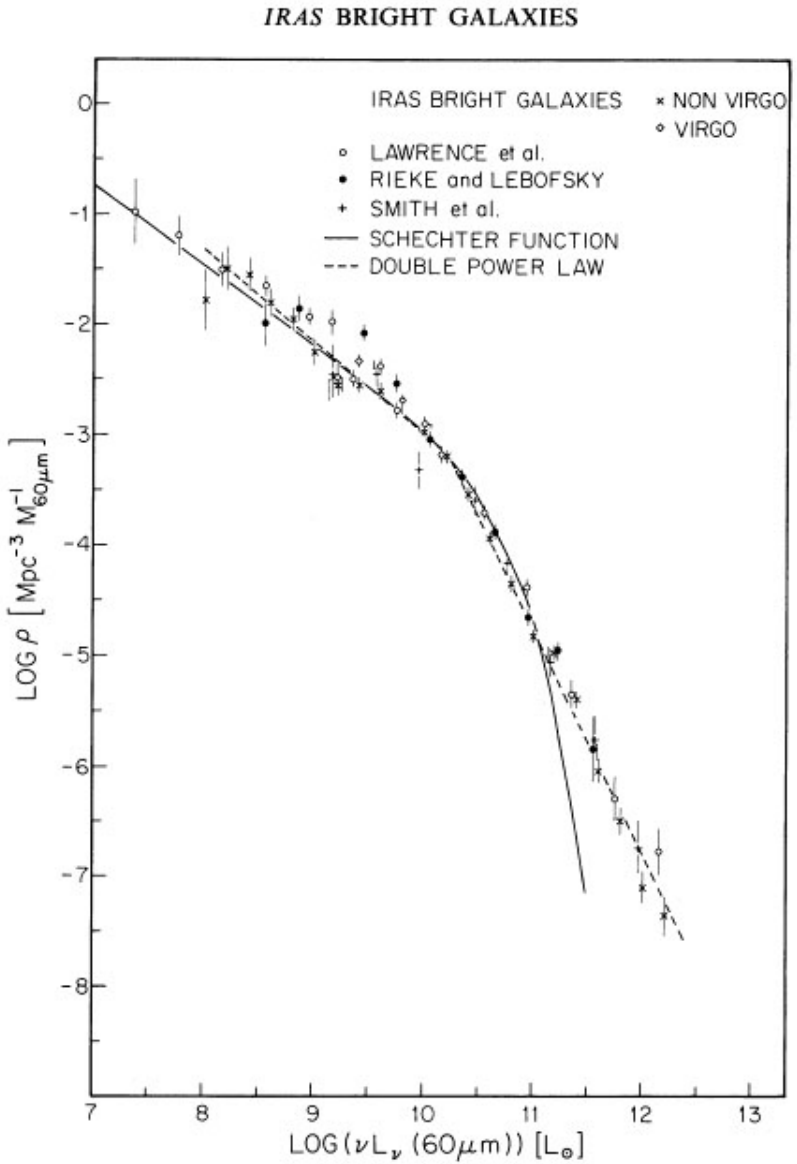


Long Wavelength Differential Counts:

Illustrating the Need for Evolution of the Infrared Luminosity Function

Elbaz et al. 1999, Serjeant et al. 2000 , Dole et al 2001, Efstathiou et al. 2000, Blain et al. 1999, Eales et al. 2000, Barger et al. 1999

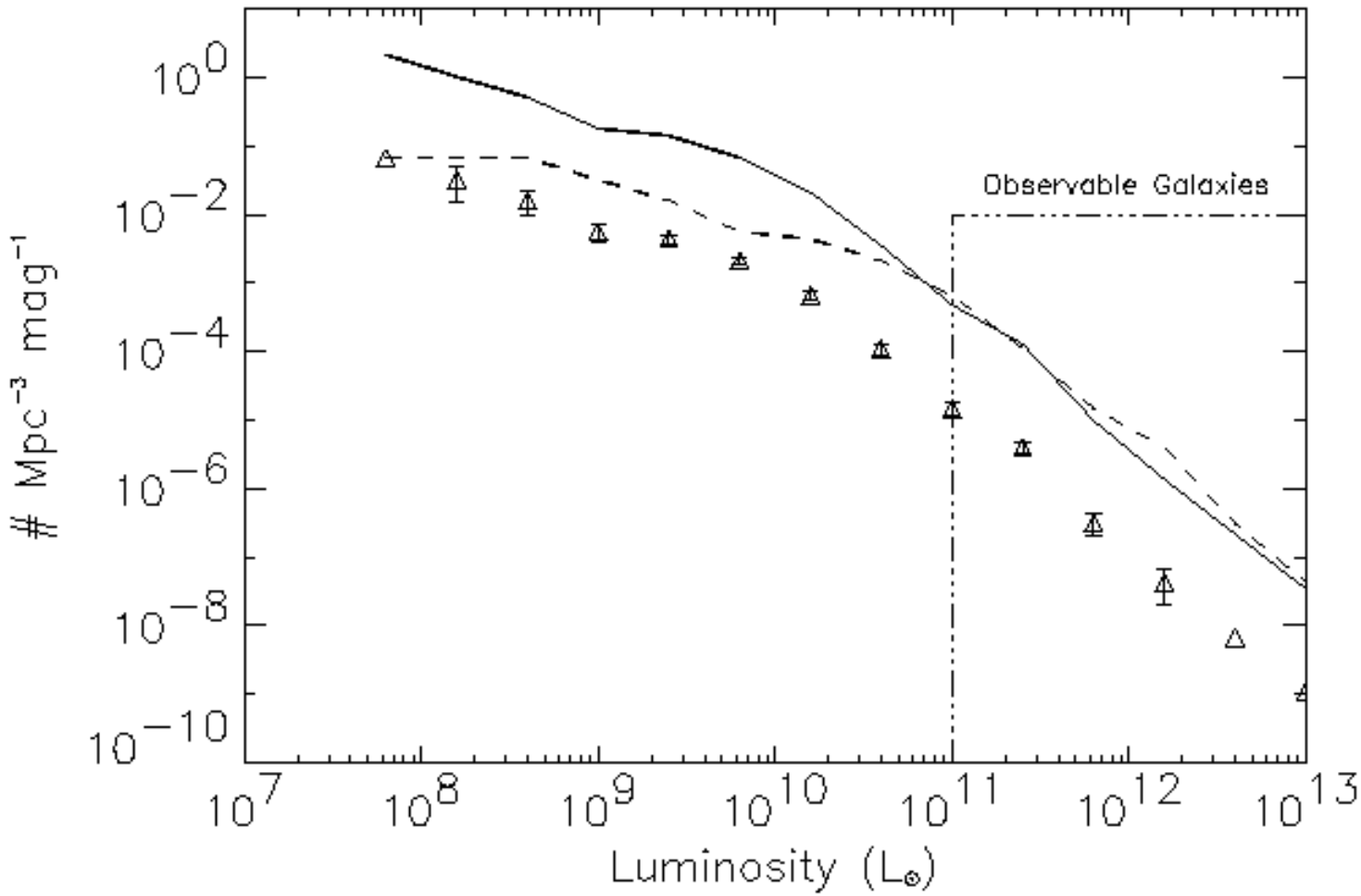
What Part of the Luminosity Function is Evolving ?

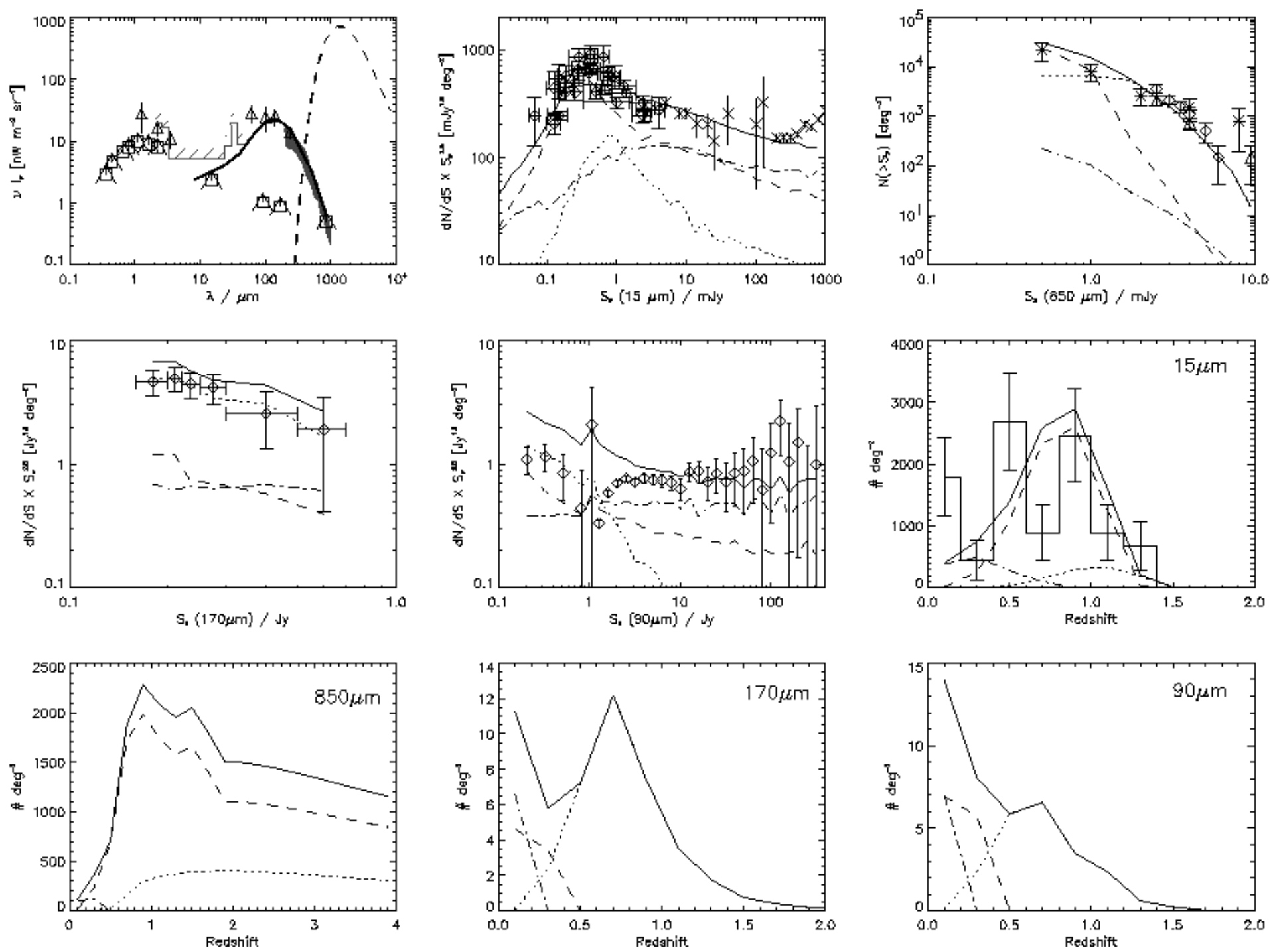


Soifer et al. 1987

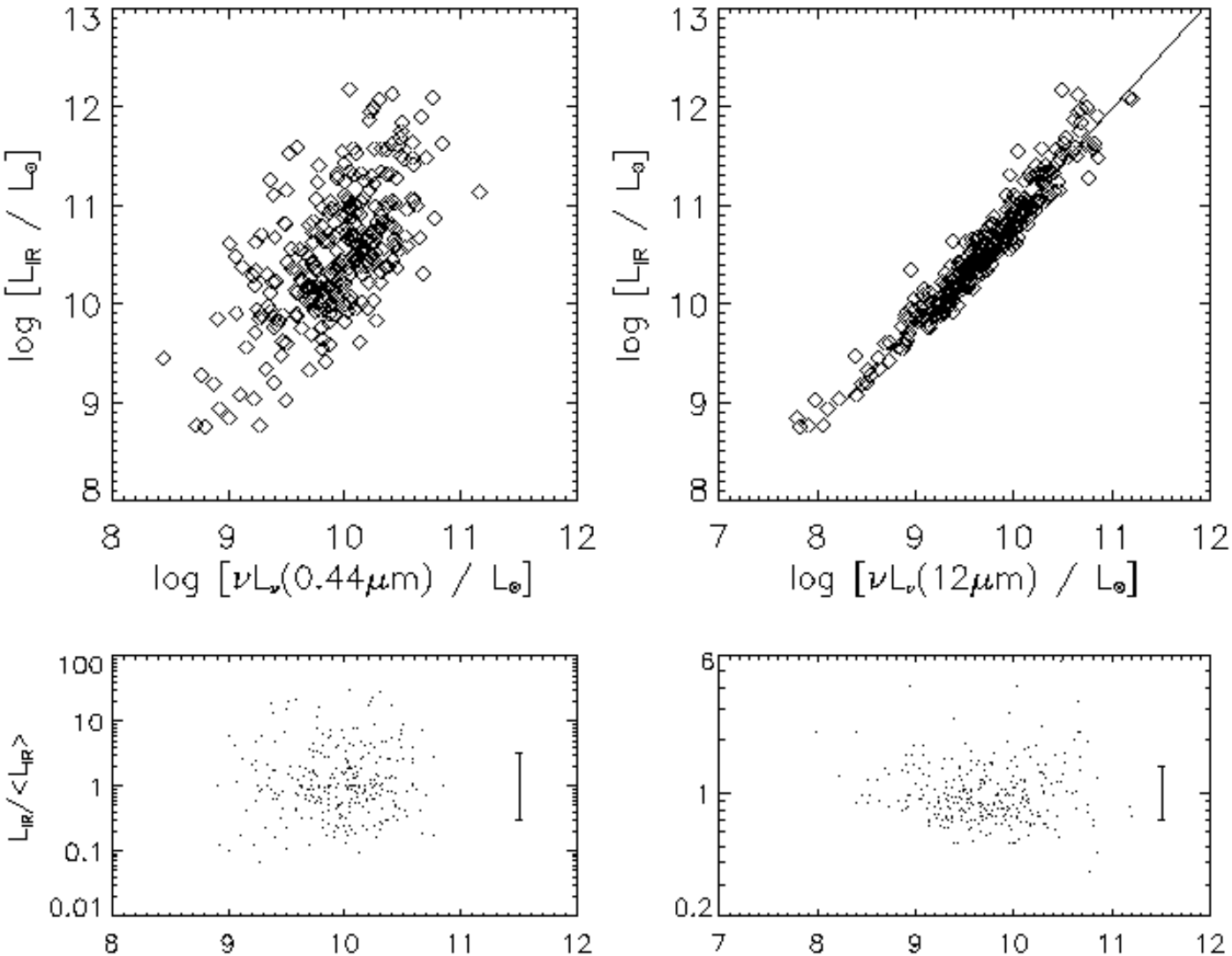
Degeneracy in Evolution Models and Extrapolations from the bright end of LF

Evolution could be in Luminosity, Density or a Combination of Both

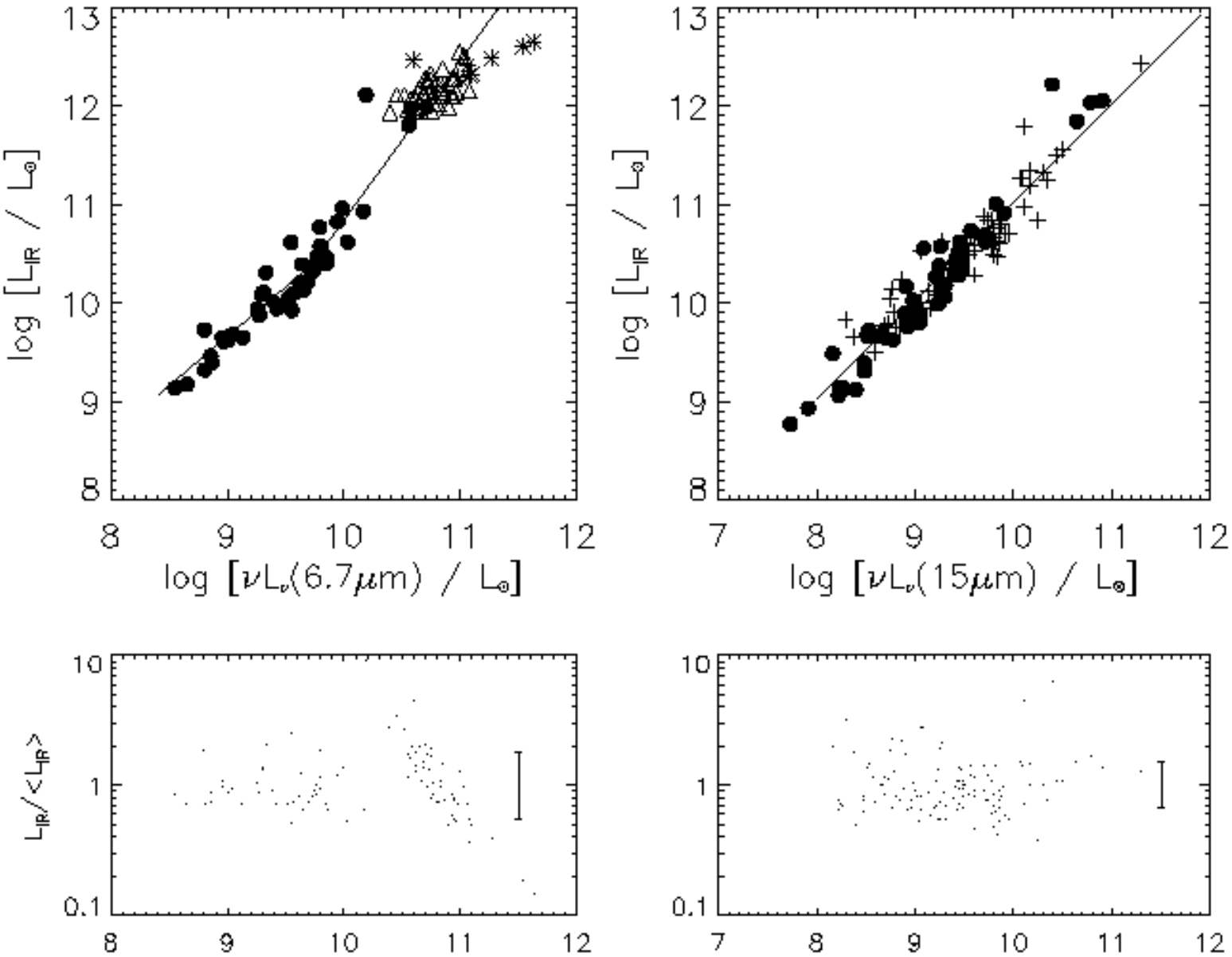



λ / μm
S_ν (15 μm) / mJy
S_ν (850 μm) / mJy
S_ν (170μm) / Jy
S_ν (90μm) / Jy
15μm
850μm
170μm
90μm
Redshift
deg⁻²

Assumptions: Galaxy SEDs are not changing with redshift

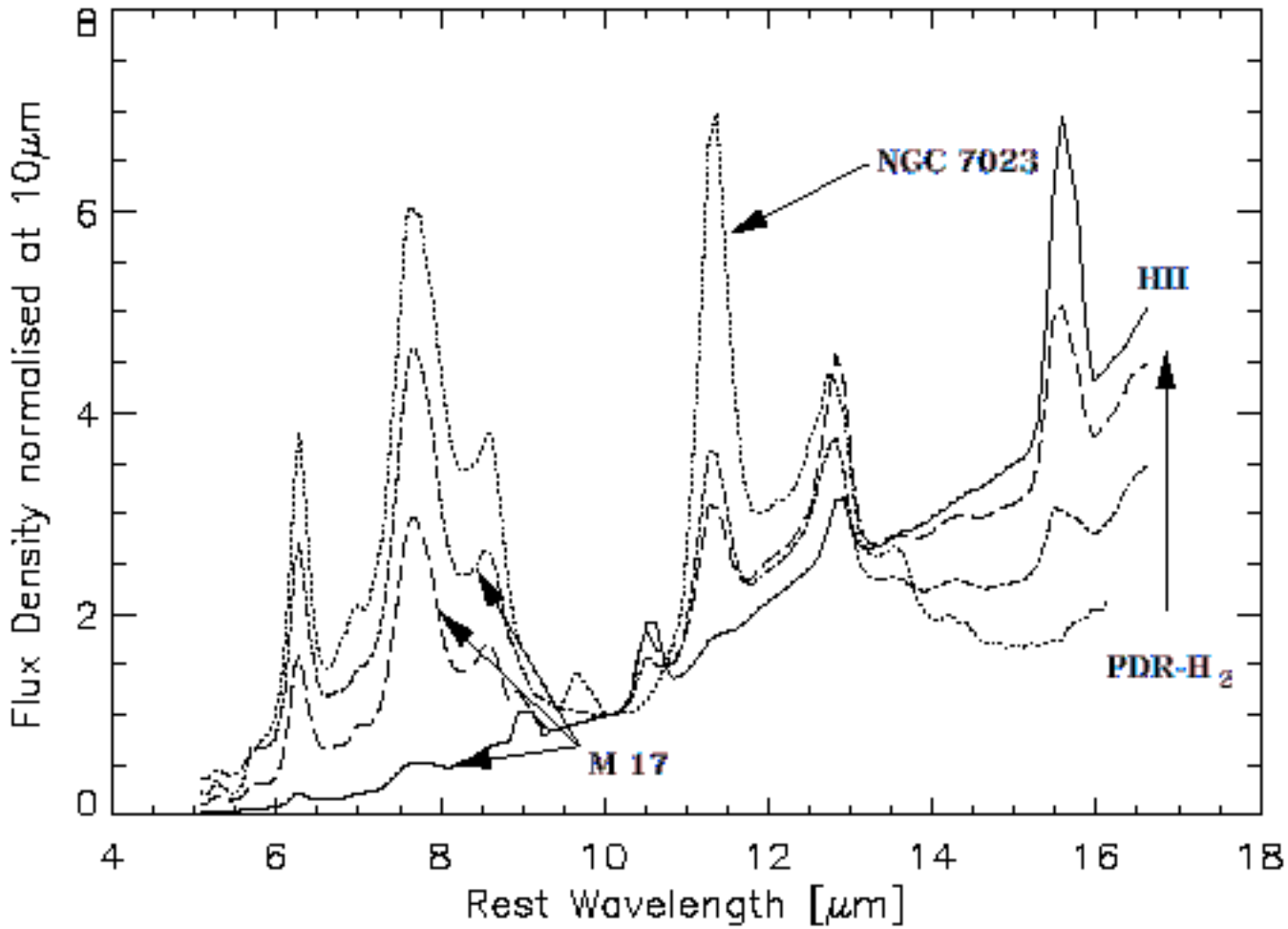


IRAS BGS: Soifer et al. 1987



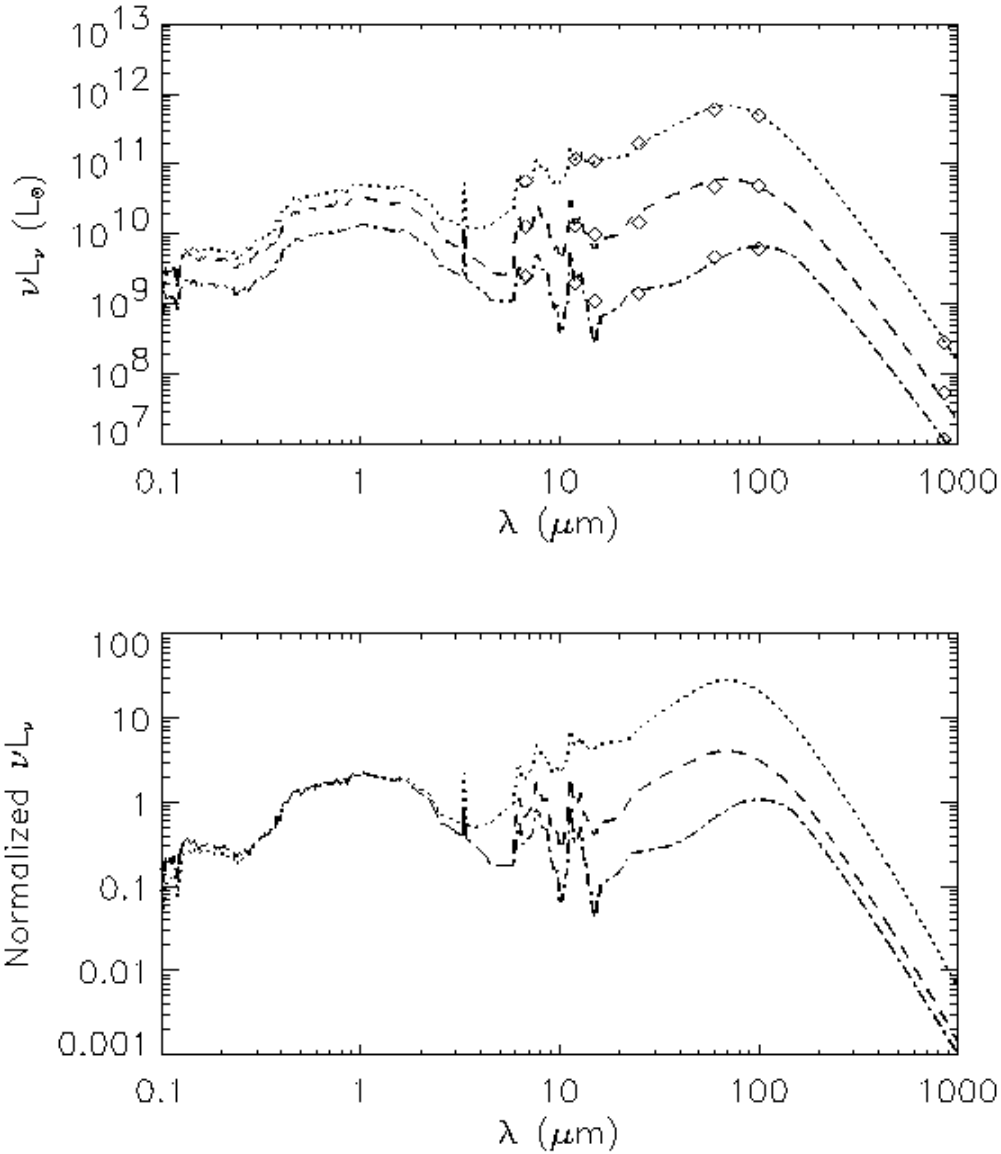
Rigopoulou et al 1999, Tran et al. 2001, Chanial et al. 2001, Aussel et al. 2000

PAH Spectrum: Possible Size/Metallicity Dependence ?



Laurent et al. 2000; Li & Draine 2001

Over-reliance on Template Spectral Energy Distribution



- Three lines are for typical ULIGs, LIGs and normal/starburst galaxies with $L_{IR}<10^{11}L_{\odot}$.
- The templates reproduce the observed trend in mid- to far-infrared luminosities seen for local galaxies.
- But, dust has multiple Temperature components.

Without knowing Dust Temperature, cannot pinpoint Luminosity or mm-z

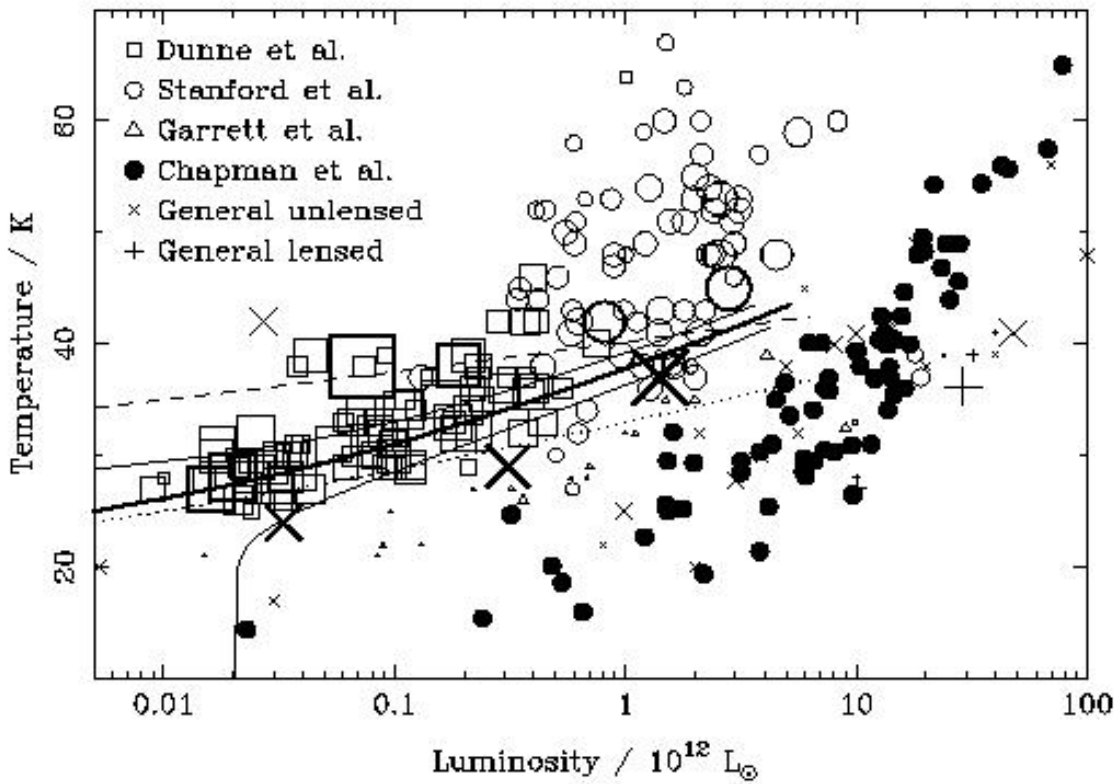
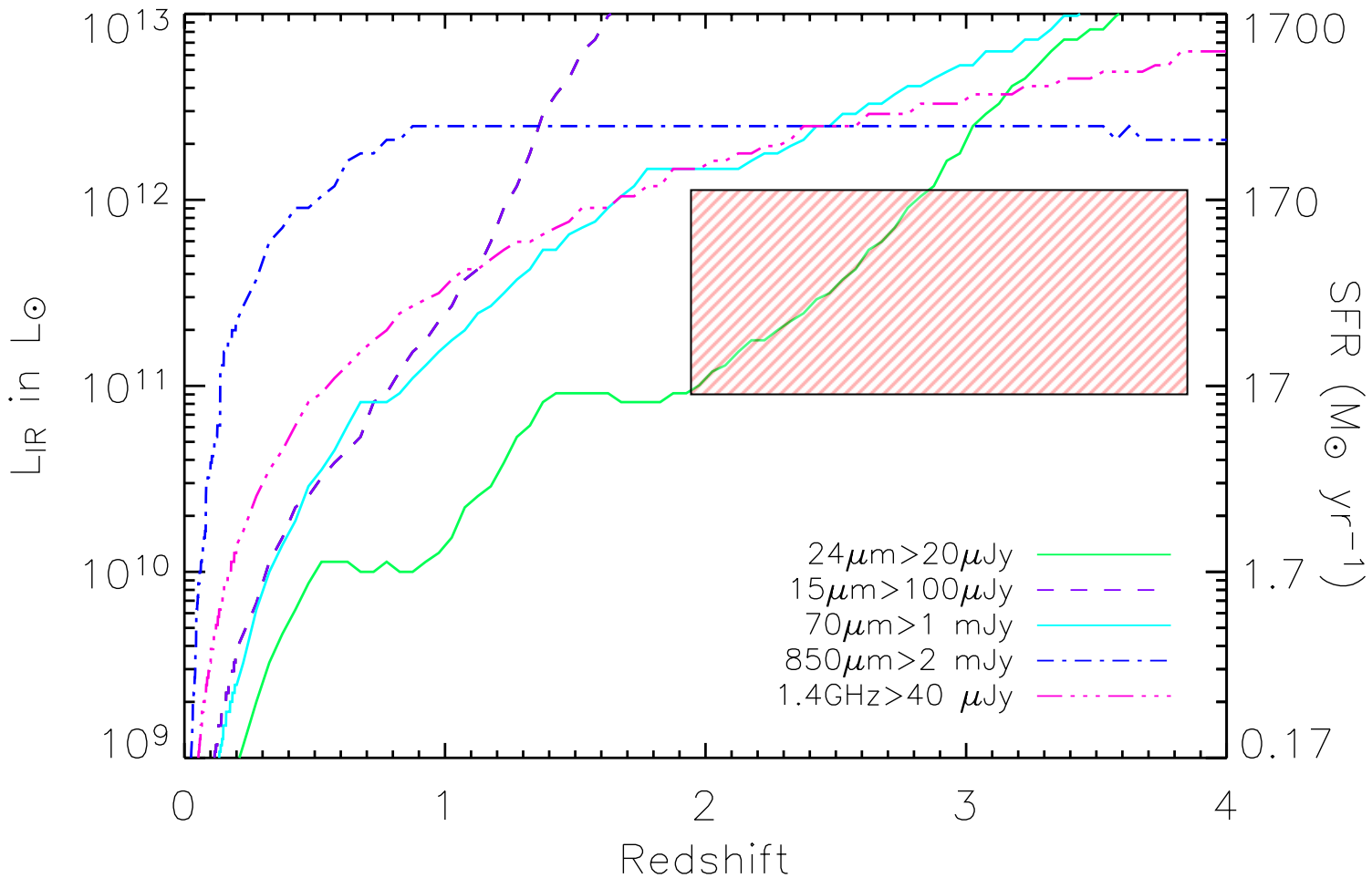
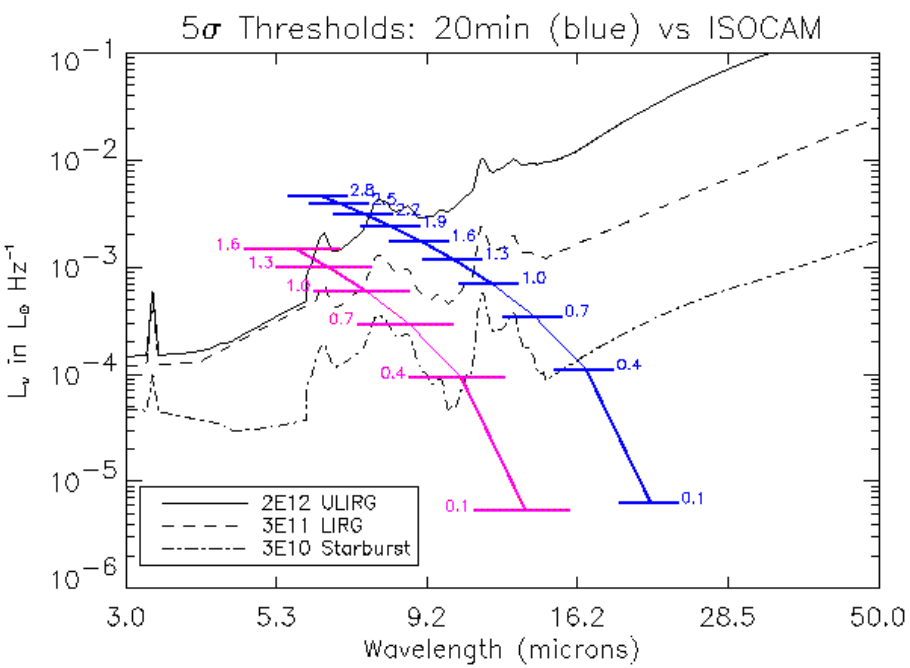


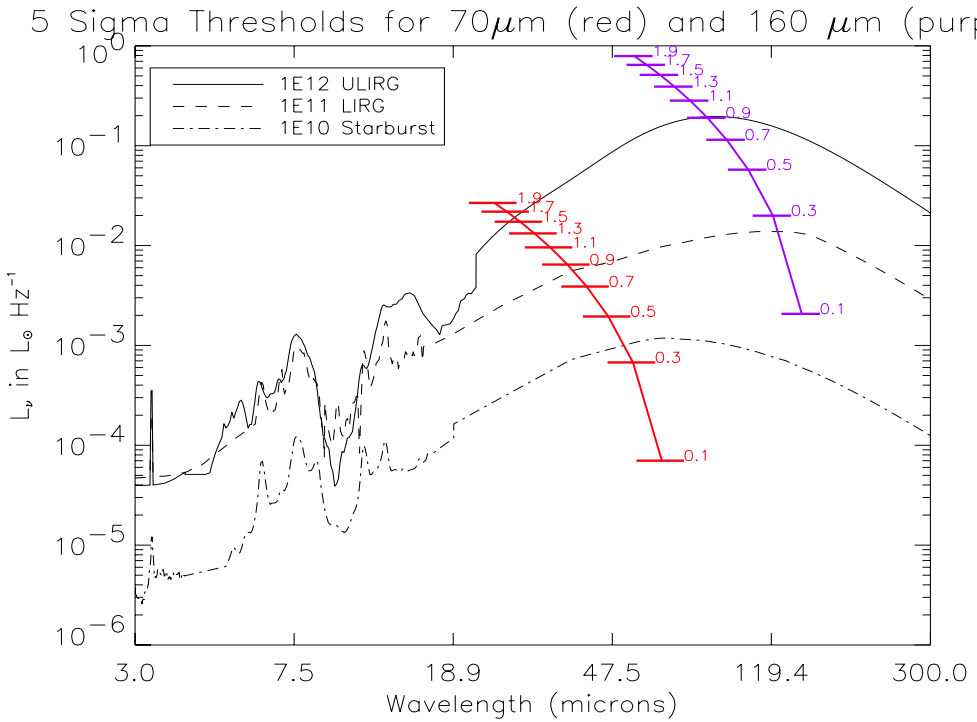
FIG. 1.— A range of luminosity L and temperature T_d values determined for well-studied dusty galaxies at a variety of redshifts: low-redshift *IRAS* galaxies – open squares (Dunne et al. 2000); moderate-redshift very luminous *IRAS* galaxies – open circles (Stanford et al. 2000); high-redshift *ISO* galaxies – empty triangles (Garrett et al. 2001); galaxies with well-determined SEDs from a wide variety of sources (including SCUBA and *ISO* surveys) – diagonal crosses represent a selection of gravitational lenses, while vertical crosses represent unlensed galaxies (for both see BBC); and spectroscopically identified SMGs – filled circles (Chapman et al. 2003, 2004a). The sample represented by diagonal crosses includes M82, the Milky Way, NGC 958 and Arp220, which are shown by the largest crosses between 2×10^{10} $L_\odot$ and 1.6×10^{12} $L_\odot$ respectively. For the non-Chapman samples large symbols reflect more accurate determinations: see BBC for a description of the errors for these samples. See Fig. 2 for uncertainties in the estimates for the Chapman et al. sample, for which all symbols are the same size. The thick solid line shows the result derived by Chapman et al. (2003a) for the L–T_d values of low-redshift *IRAS* galaxies. The interquartile range for this sample is bracketed by the two thinner solid lines, whose separation agrees well with the range of properties of the Dunne et al. sample. The dashed and dotted lines show the fits obtained to merging and quiescent low-redshift *IRAS* galaxy data respectively by Barnard (2002).

Sensitivity of MIR/FIR Observations



Sensitivity of Deep Spitzer Surveys





The UV-slope Technique: Large Uncertainties

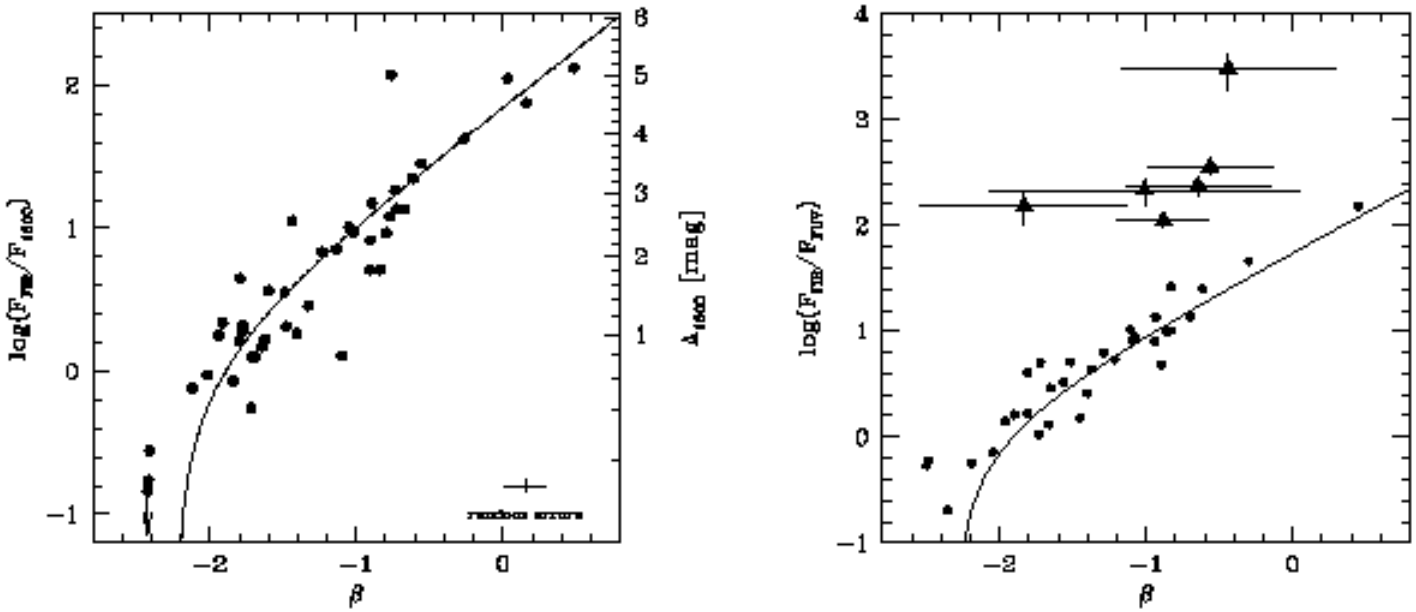
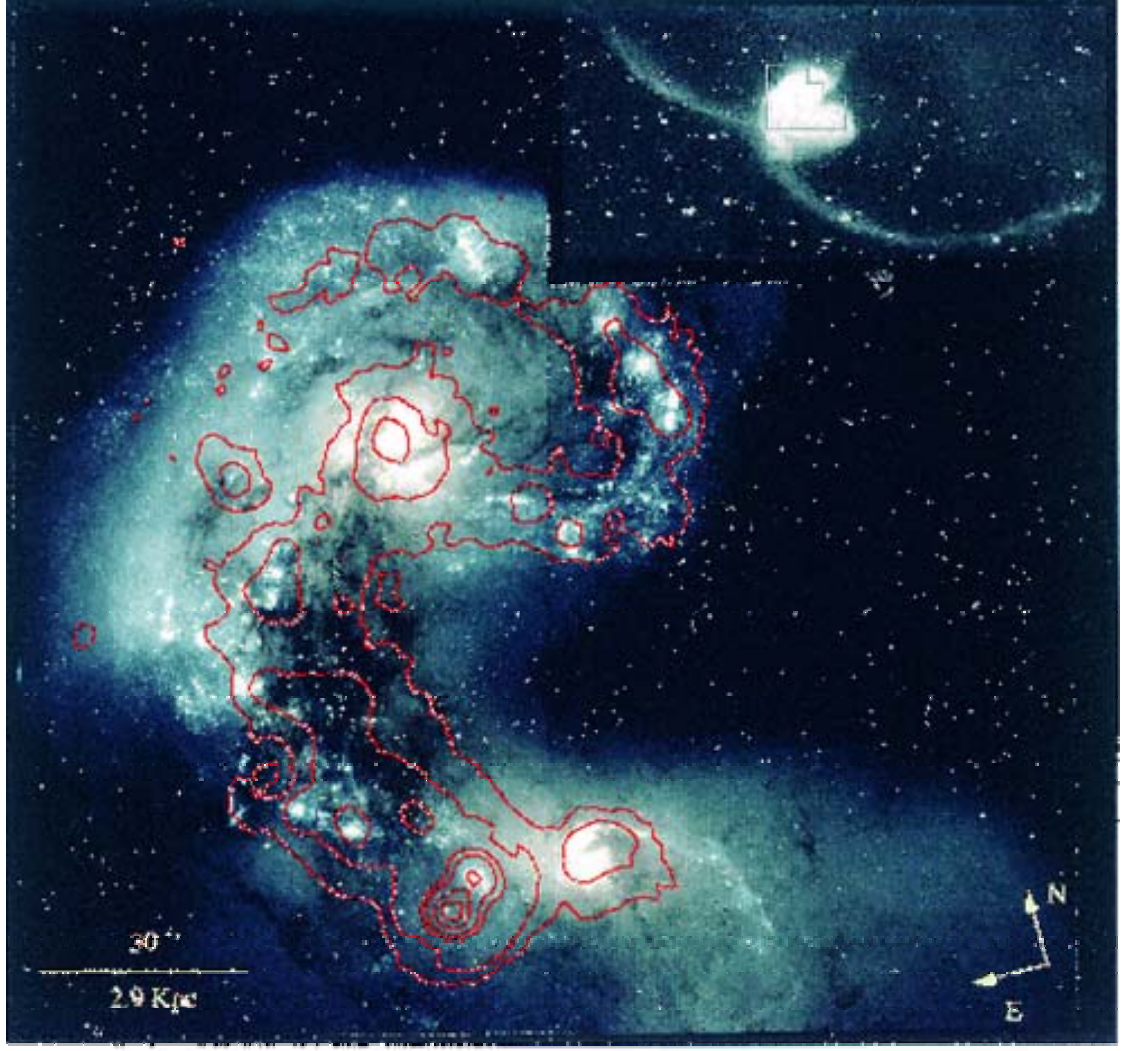


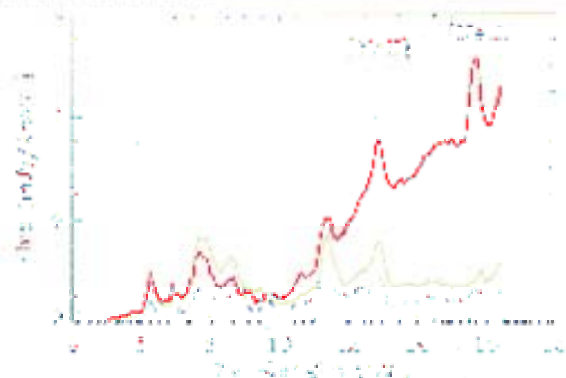
Figure 1. (Left) The $IRX \equiv F_{\rm FIR}/F_{\rm UV}$ versus β relationship of local starbursts observed by IUE (Meurer et al. 1999). Here the UV flux is measured at $\lambda_0 = 1600\mathring{A}$, and the left axis converts IRX to the effective absorption A_{1600} in magnitudes.

Figure 2. (Right) The IRX-β plot for ULIGs (triangles) in relation to the IUE starbursts. Here β and the UV flux are measured photometrically through the actual or synthetic STIS bandpasses.

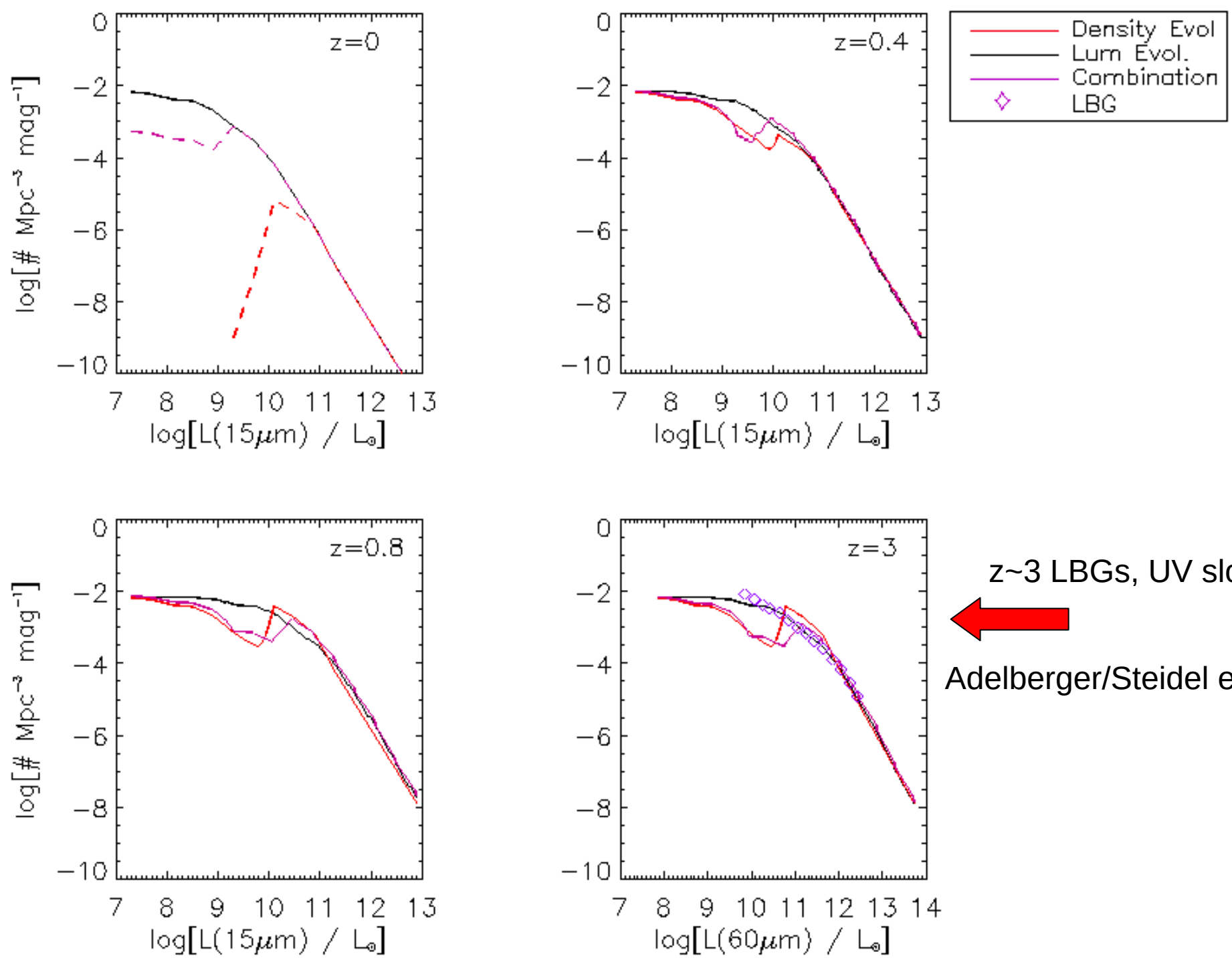
Meurer et al. 1999, 2000



About 50% of the integrated MIR luminosity comes from regions that are inconspicuous at visible wavelengths.
$L_{IR} \sim 10^{11}$



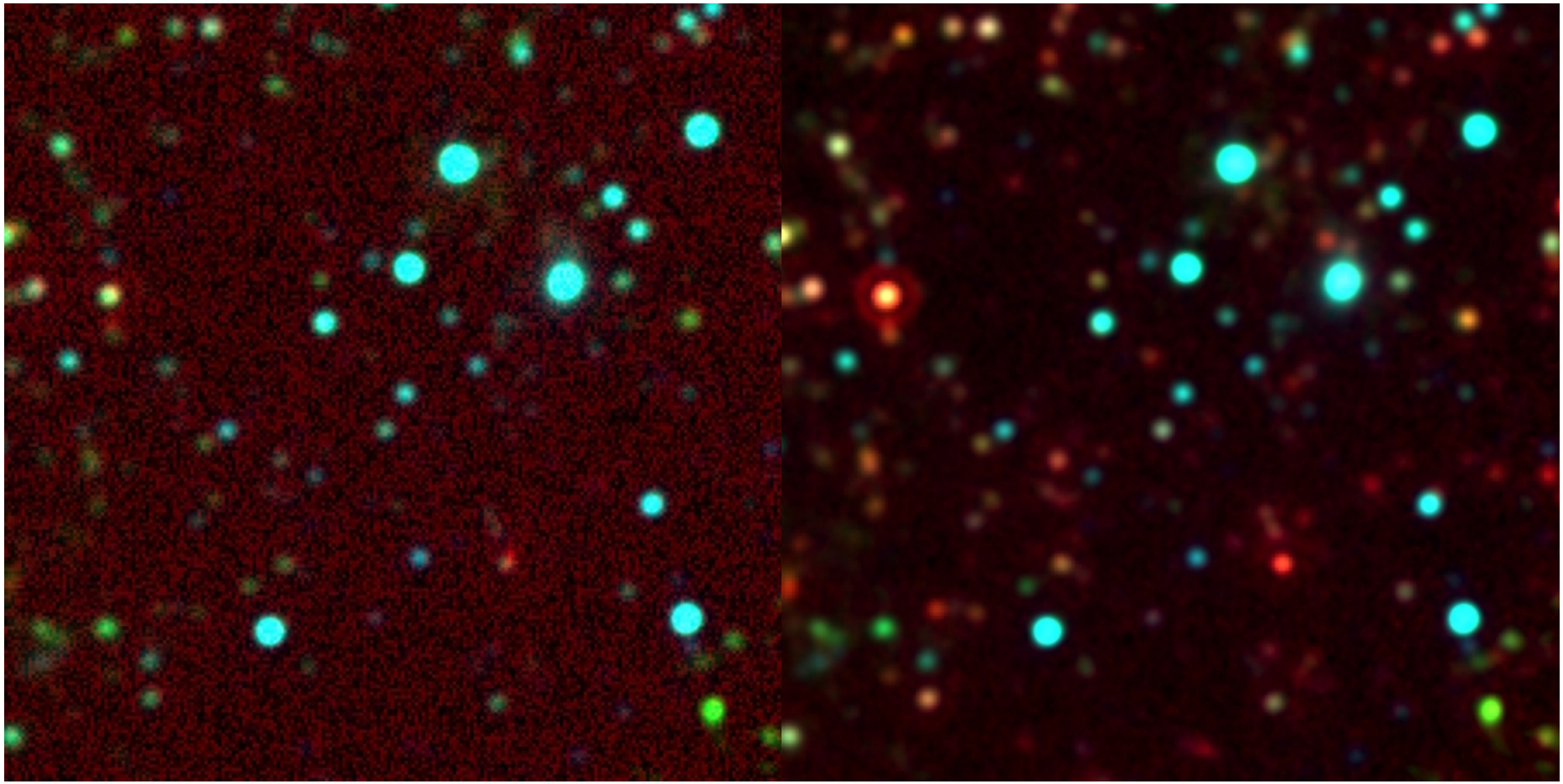
Mirabel et al. 1998



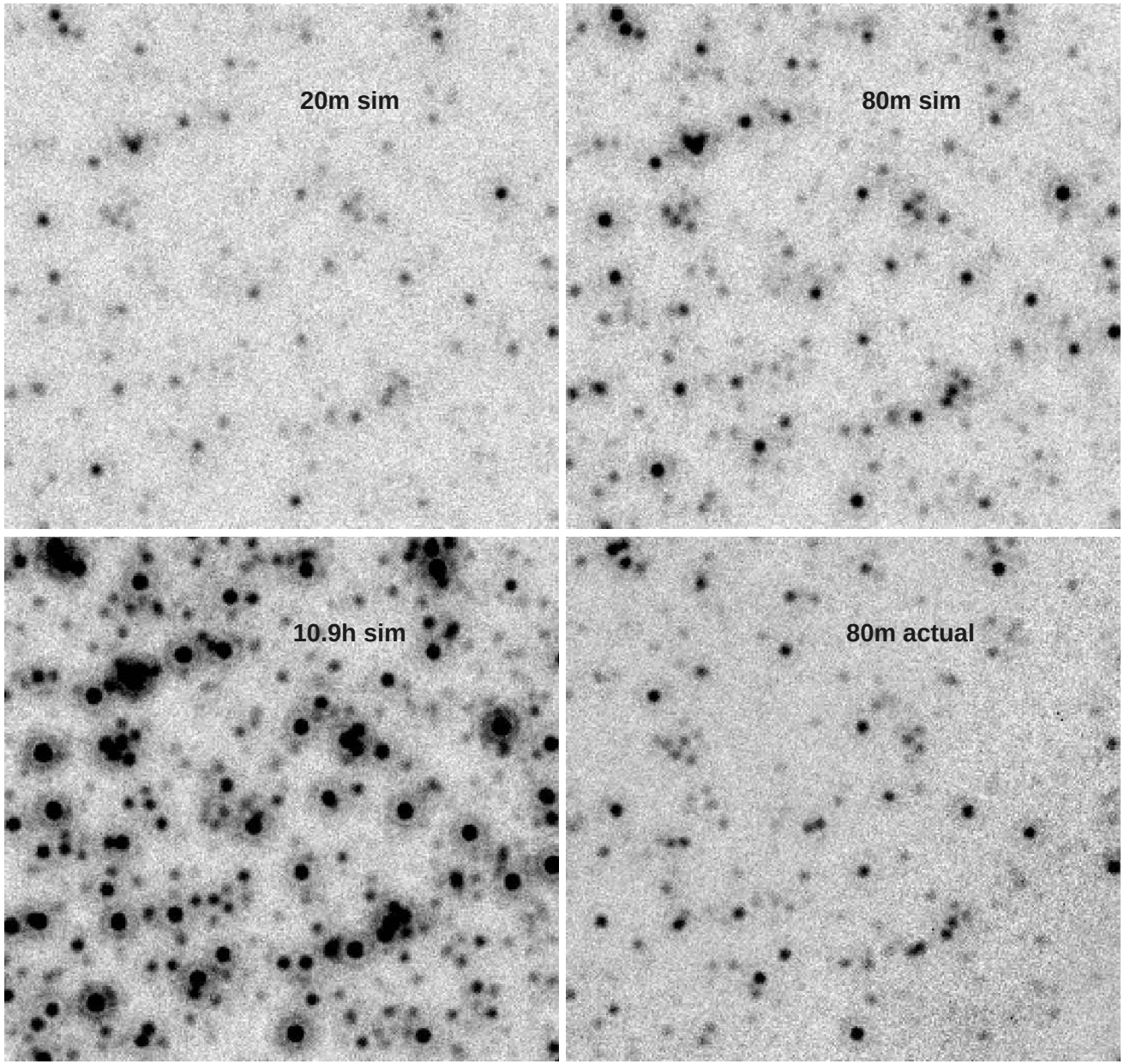
z~3 LBGs, UV slope

Adelberger/Steidel etc.

Deepest 24 micron view yet with Spitzer



Chary et al. 2004



10h GOODS (sims)

80m ELAIS-N1 data

De-blending techniques using priors

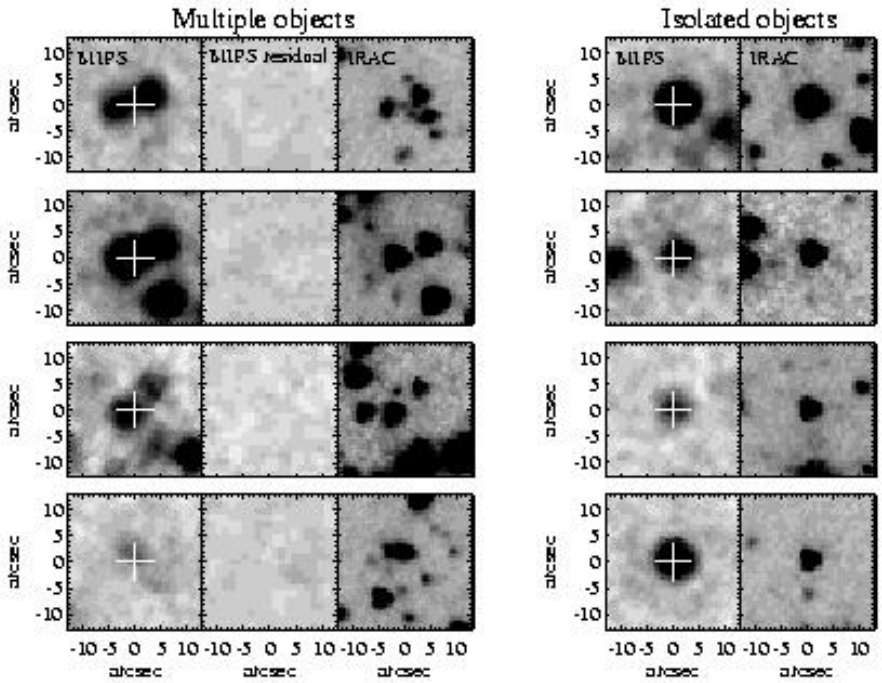
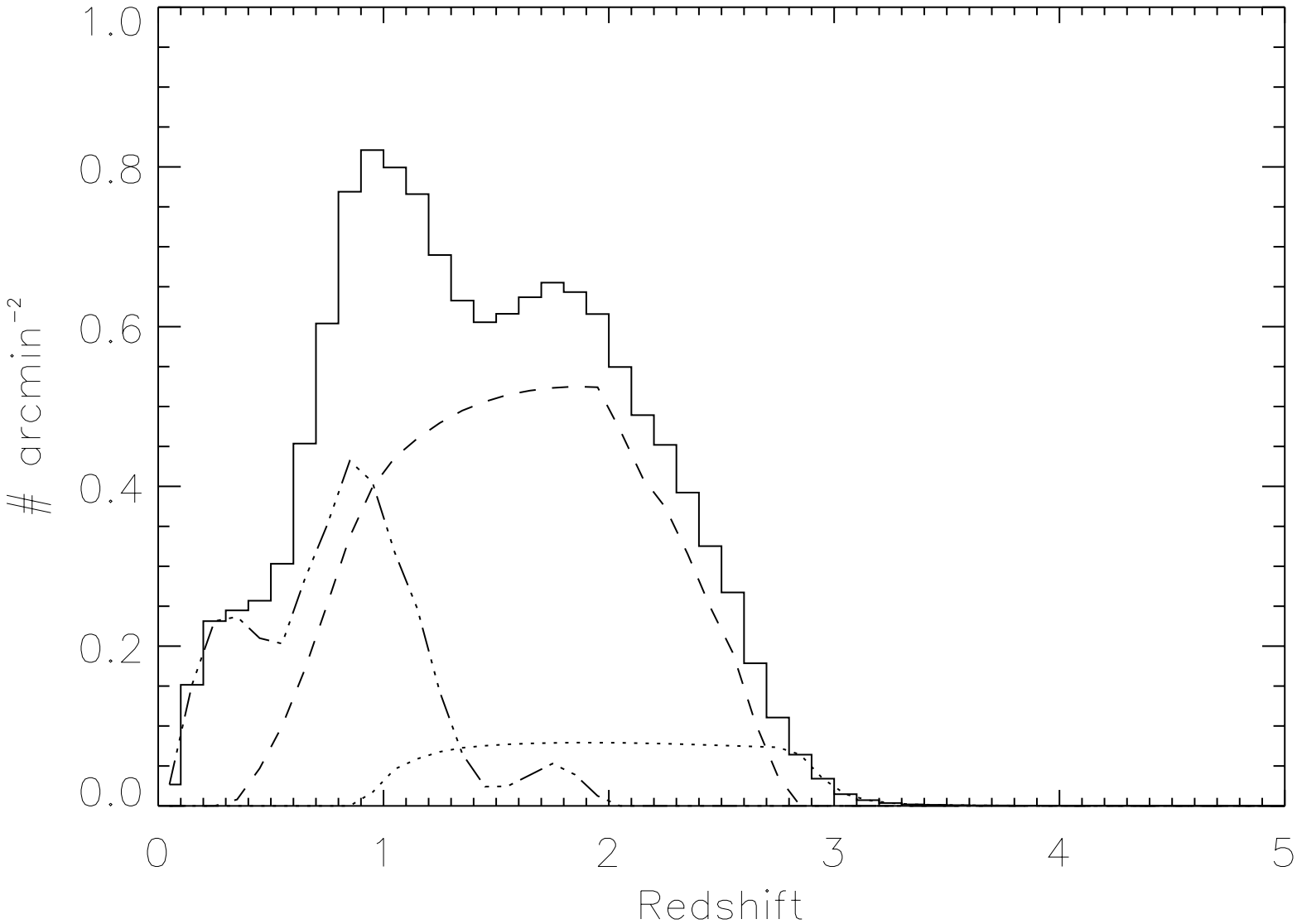


Fig. 1.— MIPS sources and their IRAC counterparts. At left we show four examples of MIPS sources (leftmost column of 3) which appear to arise from the combination of flux from two or more IRAC–detected objects (rightmost column of 3). In each case, our MIPS catalog detected only a single MIPS source, whose centroid is marked with a cross. The correct IRAC counterparts, which are clearly recognized by eye, fall more than 3″ away and thus are missed by our matching criterion. 6.5% of the MIPS sources in our catalog fall into this category. The center column shows the results of DAOPHOT fitting and subtraction of the MIPS source(s) using the IRAC positions as priors to constrain the number and location of 24μm sources (see also Figure 5). At right, we show four examples of the 85% of MIPS sources for which IRAC counterparts were automatically found by the MIPS/IRAC catalog matching procedure.

Expected z-distribution of 24 μm sources in the 20-500 μJy flux range based on evolutionary models: Finally, LIGs at z=2.5 !



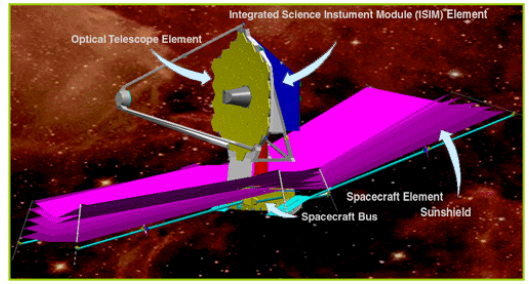
SOFIA Ultradeep ?

- x3 longer wavelength than Spitzer/70μm but x3 larger aperture as well.

- Better constraints on the dust temperature and thereby the luminosity of the MIPS sources at z<3.

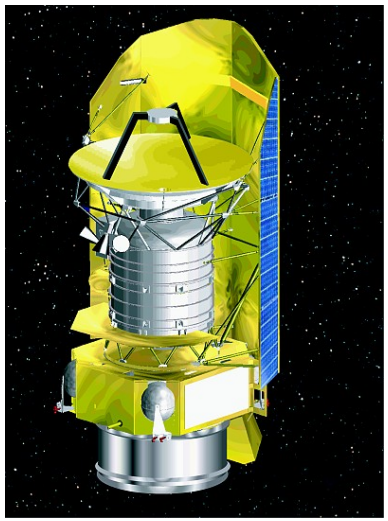
- Unlikely to detect a new population of sources in continuum observations but superb spectral capabilities between atmospheric lines.

JWST 25 μm



- Confusion will not be an issue
- However, minimal utility in terms of dusty star-formation since k-correction redshifts the 6.7micron PAH out of the window.
- GOODS will resolve the emission out to L* anyway.
- Would like JWST to be operating up to 40 microns because can then detect MIR dust features out to z~5 when the metallicity of the Universe was [Fe/H]=-3.5
- Also, in combination with ALMA will help constrain the bolometric dust SEDs. If anything, probably more MIR emission (and less FIR) at these redshifts because of smaller grain size.
- However, UV luminosity density is higher => VSG dust destruction ?

The Future of Dusty Galaxy Evolution at 2<z<4 is really ALMA



- 3.5m, 60-700 μm
- 2007, ESA

ALMA at Chajnantor
(Courtesy NAOJ)

ESO PR Photo 14/01 (6 April 2001)

© European Southern Observatory

- 64, 12m dishes
- 150m-12 km baseline
- 5000m up in Chile
- Longwards of 300 μm upto 70 GHz
- 2011